Confirmation of non-thermal hard X–ray excess in the Coma cluster from two epoch observations

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ABSTRACT

We report the hard X–ray spectrum of the Coma cluster obtained using the PDS data of two independent *BeppoSAX* observations performed with a time interval of about three years. In both the spectra a non thermal excess with respect to the thermal emission is present at a confidence level of $\sim 3.4\sigma$. The combined spectrum obtained by adding up the two spectra allows a measurement of the excess at the level of $\sim 4.8\sigma$ at energies above 20 keV. The analysis of the full *BeppoSAX* data set provides a revised non-thermal X-ray flux which is slightly lower than that previously estimated (Fusco-Femiano *et al.* 1999) and in agreement with that measured by two *RXTE* observations. The analysis of the offset fields in our Coma observations provides a possible flux determination of the BL Lac object 1ES 1255+244.

Subject headings: cosmic microwave background — galaxies: clusters: individual (Coma) — magnetic fields — radiation mechanisms: non-thermal — X–rays: galaxies: BL Lacertae objects: individual (1ES 1255+244)

1. Introduction

In the hierarchical scenario of structure formation, clusters of galaxies form by the gravitational merger of sub-clusters and groups. Numerical simulations of large scale structure formation indicate that this class of objects undergo several merger processes as they form (West, Villumsen, & Dekel 1991; Katz & White 1993). Cluster mergers are highly energetic events and the associated large scale shocks and turbulence could provide the ingredients necessary to the formation of extended radio regions (radio halos or relics) detected so far in a limited number of clusters, namely a magnetic field amplification and particle re-acceleration (Tribble 1993; Roettiger, Burns, & Stone 1999; Roettiger, Stone, & Burns 1999; Cavaliere, Menci, & Tozzi 1999; Brunetti *et al.* 2001; Fujita, Takizawa, & Sarazin 2003). Clusters of galaxies with detected diffuse radio emission indeed show significant evidence of merger activity. The existence of Mpc-scale radio halos or relics combined with the relatively short radiative lifetimes of the electrons ($\sim 10^8$ yrs) suggests an in-situ electron re-acceleration induced by a very recent or current merger event (Markevitch & Vikhlinin 2001).

The presence of large radio regions could be related to the origin of the non-thermal hard X–ray (HXR) emission detected in the Coma cluster (Fusco-Femiano *et al.* 1999; Rephaeli,

Gruber, & Blanco 1999; Rephaeli & Gruber 2002) and Abell 2256 (Fusco-Femiano *et al.* 2000; Rephaeli & Gruber 2003) by *BeppoSAX* and *RXTE* and, at lower confidence level, by *BeppoSAX* in A754 (Fusco-Femiano *et al.* 2003). The most likely interpretation of the non-thermal HXR radiation is inverse Compton (IC) emission by the same radio synchrotron electrons scattering the cosmic microwave background (CMB) photons. However, one cannot completely exclude the possibility that the non-thermal emission detected by *BeppoSAX* and *RXTE* may be due to the presence of obscured sources in the field of view of the detectors. The *BeppoSAX*/MECS images test this possibility only in the cluster central region of size $\sim 30'$ in radius while the *BeppoSAX*/PDS (Frontera *et al.* 1997), which is able to detected HXR radiation in the energy range 15–200 keV, has a larger field of view (FWHM $\sim 1.3°$). The probability to find obscured sources, like Circinus (Matt *et al.* 1999) very active at high energies, in the field of view of the PDS is estimated to be of the order of 10% (Kaastra 1999; Fusco-Femiano *et al.* 2002). Future deep observations by IBIS on-board *INTEGRAL* with a spatial resolution of $\sim 12'$ can definitely resolve this uncertainty. A different mechanism given by non-thermal bremsstrahlung from supra-thermal electrons formed through the current acceleration of the thermal gas (Enßlin, Lieu, & Biermann 1999; Dogiel 2000; Dolag & Enßlin 2000; Sarazin & Kempner 2000; Blasi 2000; Liang, Dogiel, & Birkinshaw 2002) requires an unrealistically high energy input in order to maintain the HXR emission for more than 10^8 yrs (Petrosian 2001;2002). In conclusion, the origin of the detected non-thermal HXR excesses in some clusters of galaxies seems to be restricted to a diffuse IC emission or to the presence of point sources in the field of view of the PDS.

In this Letter, we present the results of a long *BeppoSAX* observation of ~ 300 ksec that confirms the presence of a non-thermal HXR tail in the spectrum of the Coma cluster in agreement with the detection obtained by a previous shorter observation of ~ 91 ksec, after data re-analysis of the first observation slightly modified the numerical results reported in Fusco-Femiano *et al.* 1999, but not the general conclusions. Finally, we show the combined spectrum obtained by summing the spectra of the two observations.

Throughout this Letter we assume a Hubble constant of $H_o = 50$ km s^{-1} Mpc^{-1} h_{50} and $q_0 = 1/2$, so that an angular distance of $1'$ corresponds to 40.6 kpc ($z_{Coma} = 0.0232$). Quoted confidence intervals are at 90% level, if not otherwise specified.

2. PDS Data Reduction and Results

The Coma cluster was observed for the first time in December 1997 for ∼91 ksec and re-observed in December 2000 for ∼300 ksec. The pointing coordinates of *BeppoSAX* are at J(2000): $\alpha:\ 12^h\ 58^m\ 52^s$; $\delta:\ +27°\ 58'\ 54''$. The total effective exposure times of the

PDS in the two observations were 44.5 ksec and 122.2 ksec, respectively (hereafter OBS1 and OBS2).

The PDS spectra of both the observations were extracted using the XAS v2.1 package (Chiappetti & Dal Fiume 1997). The choice of using this software is dictated by the non standard pipeline needed to extract the net count spectra (see below). Because our Institute (i.e., IASF/Bologna) was in charge of the design, construction and maintenance of the PDS, and we developed and tested the XAS package, specifically created to handle the PDS peculiarities (while the SAXDAS package, used for the standard analysis, is more suitable for handling imaging instruments, like MECS and LECS), we felt more confident in using XAS for the PDS analysis.

Since the source is rather faint in the PDS band (∼5 mCrab in 15–100 keV) a careful check of the background subtraction must be performed. The background sampling was performed by making use of the default rocking law of the two PDS collimators that samples ON/+OFF, ON/–OFF fields for each collimator with a dwell time of 96 sec (Frontera *et al.* 1997a). When one collimator is pointing ON source, the other collimator is pointing toward one of the two OFF positions. Initially, we used the standard procedure to obtain PDS spectra (Dal Fiume *et al.* 1997); this procedure consists of extracting one accumulated spectrum for each unit for each collimator position. We then checked the two independently accumulated background spectra in the two different +/–OFF sky directions, offset by 210′ with respect to the on-axis pointing direction (+OFF pointing: $\alpha:\ 12^h\ 58^m\ 57.8^s$; $\delta:\ +24^\circ\ 28'\ 55''.1$ –OFF pointing: $\alpha:\ 12^h\ 58^m\ 47.0^s$; $\delta:\ +31^\circ\ 28'\ 54''.7$).

The comparison between the two accumulated backgrounds (difference between the +OFF and –OFF count rate spectra) shows that for OBS1 the difference is compatible with zero (0.044 ± 0.047 cts/s for a background level of 21.66 ± 0.02 cts/s in 15–100 keV), while for the longer, more sensitive OBS2, there is an excess of 0.064 ± 0.021 cts/s (background 16.76 ± 0.01 cts/s)[1]. A careful check of possible variable sources in the PDS offset fields lead our attention to the BL Lac source 1ES 1255+244, present in the +OFF field. Luckily, this same source was observed by *BeppoSAX* on May 1998 in the framework of a spectral survey of BL Lacs by Beckmann *et al.* (2002), who, somewhat surprisingly, state "for 1ES 1255+244 there are no PDS data". Indeed, we retrieved the raw data from the ASI Scientific Data Center, extracted the PDS spectrum (the background has to be evaluated only on one offset field because the other is pointed exactly on Coma — the two sources are contaminating each other!) and found that the source is quite faint, consistent with zero flux being detected.

[1]The ∼20% variation in the PDS background is due to the *BeppoSAX* orbital decay: the lower orbit for OBS2 increased the shielding to ambient particles, therefore lowering the diffuse background.

Because of the very short exposure time (~ 3 ksec) it is only possible to give a 2σ upper limit of 0.26 cts/s in 15–100 keV, corresponding to 1.6 mCrab, however compatible with the background excess measured in OBS2.

It is worth noticing that it is possible to derive a more stringent upper limit on the X–ray flux from 1ES 1255+44 at the time of our Coma OBS2 by assuming that all the contamination in the +OFF field comes from this source. It is straightforward to show that the 0.064 ± 0.021 cts/s excess translates into 428 ± 424 net counts when one takes into account the much shorter BL Lac observation (3340 sec) compared to our OBS2 and an upward factor two correction due to the $\sim 40'$ off-axis position of the source, corresponding to a 50% intensity reduction because of the triangular collimator response (Frontera *et al.* 1997b). At its face value this is consistent with the run of PDS counts as compared to the MECS counts in the BL Lac sample studied by Beckmann *et al.* (2002), barring time variability effects.

Returning to the Coma observations, to remain on the safe side we decided to exclude the +OFF field in the background evaluation, and consider only the –OFF field as the "uncontaminated" background for both the Coma observations. Moreover, just in the center of the +OFF field is also present the extremely weak ROSAT source RX J125847.1+242741. However, in section 3 we also report the level of confidence of the non-thermal excess considering the average of the measured backgrounds in the two positions.

The observed count rate of OBS1 is 0.78 ± 0.03 cts/s in the 15–100 keV energy range, at a confidence level of $\sim 26\sigma$. In the first analysis the non-thermal excess with respect to the thermal bremsstrahlung emission reported by the PDS was at the confidence level of $\sim 4.5\sigma$. The derived non-thermal flux was $\sim 2.2 \times 10^{-11}$ erg cm^{-2} s^{-1} in the 20–80 keV energy band (assuming a photon index $\Gamma_X = 1.5$). By relating the radio and the non-thermal fluxes it was then possible to estimate a volume-averaged intracluster magnetic field $B_X \sim 0.15\mu G$, using only observables (Fusco-Femiano *et al.* 1999). It should be pointed out that a re-analysis of these data has evidenced a trivial mistake in the previous data analysis (summing three spectra, one of them was summed twice), so that the correct spectrum obtained from OBS1 shows an excess with respect to the thermal component with the average gas temperature measured by *Ginga* (8.11 ± 0.07, 90%; David *et al.* 1993) at a somewhat lower confidence level of $\sim 3.4\sigma$ (see Table 1). The fit with a single temperature gives $\sim 9.9^{+1.3}_{-1.1}$ keV, above the average gas temperature measured by *Ginga* (with a field of view comparable to that of the PDS), implying the presence of a second spectral component. The fit with two thermal components (one fixed at 8.1 keV) requires an unrealistic second temperature (> 50 keV) that strongly supports a non-thermal mechanism for the additional component present in the spectrum of the Coma cluster. If we consider a power-law for the second component, the PDS data are not able to fix the photon index, but the non-thermal flux is rather stable

against index variations. We assume a photon index $\Gamma_X = 2.0$ to derive the non-thermal flux that results to be $(2.3 \pm 1.0) \times 10^{-11}$ erg cm^{-2} s^{-1} in the 20–80 keV energy range.

The observed count rate of OBS2 is 0.72±0.02 cts/s in the 15–100 keV energy range, at the confidence level of $\sim 36\sigma$. At energies above 20 keV the spectrum shows an excess with respect to the thermal emission (kT = 8.1 keV) at a confidence level of $\sim 3.4\sigma$ (see Table 1). The fit with a single temperature gives $\sim 9.5^{+0.8}_{-0.6}$ keV. Also OBS2 indicates the presence of an additional spectral feature and also in this case the fit with a second thermal component requires unrealistic values for the temperature. The non-thermal flux (Γ_X=2.0) is $(1.3^{+0.5}_{-0.6}) \times 10^{-11}$ erg cm^{-2} s^{-1} in the band 20–80 keV, consistent with the flux reported in OBS1. The non-thermal fluxes are (marginally) consistent also at a 68% confidence level: $(2.3 \pm 0.7) \times 10^{-11}$ erg cm^{-2} s^{-1} in the first observation and $(1.3^{+0.3}_{-0.4}) \times 10^{-11}$ erg cm^{-2} s^{-1} in the second one.

The combined spectrum is obtained by summing the spectra of the two observations (see Fig. 1). The total count rate is 0.740 ± 0.017 cts/s in the 15–100 keV energy range, at the confidence level of $\sim 44\sigma$. At energies >20 keV the HXR excess is at the confidence level of $\sim 4.8\sigma$ (see Table 1). Even the inclusion of a 1% systematic to the data, necessary for sources with high S/N ratio but not for faint sources like Coma (Frontera *et al.* 1997b), does not change the significance of our non-thermal HXR excess. The fit with a single thermal component gives 9.7±0.6 keV, well above the average gas temperature measured by *Ginga*, with a statistically unacceptable χ^2 value (=2.1 for 8 d.o.f.). The presence of a second component is more evident from the χ^2 value that has a significant decrement when a second component, a power law, is added to the thermal component with kT=8.1 keV. The improvement passing from the first model ($\chi^2_\nu = 4.10$ for 9 d.o.f.) to the second one ($\chi^2_\nu = 1.2$ for 7 d.o.f.) is significant at more than 99.4% confidence level, according to the F-test. Also, the combined spectrum cannot be fitted with a second thermal component unless an unrealistic value for the temperature is assumed, thus supporting the non-thermal origin for this additional spectral feature. The non-thermal flux for Γ_X=2.0 is $(1.5 \pm 0.5) \times 10^{-11}$ erg cm^{-2} s^{-1} in the 20–80 keV energy range and it is rather stable assuming reasonable different values of the photon index. In fact, for Γ =1.5 the flux is $\sim 6\%$ lower and for $\Gamma = 2.5$ is $\sim 15\%$ higher.

3. Discussion

Non-thermal HXR emission has been reported in two *BeppoSAX* observations of the Coma cluster performed with a time interval of about three years. Both the observations indicate the presence of a non-thermal excess with respect to the thermal emission at a

confidence level of $\sim 3.4\sigma$. The combined spectrum obtained by adding up the two spectra gives an excess at the confidence level of $\sim 4.8\sigma$. The spectra of the two observations have been obtained using only the uncontaminated background-accumulated pointing at the [–OFF] field. However, by considering the average of the background measurements in the two sky directions in both the observations, the excess is still significant at the level of $\sim 3.9\sigma$ (observed count rate = 0.324±0.013 cts/s, model predicted rate = 0.273 cts/s). The non-thermal fluxes measured in the two observations are consistent at the 90% confidence level and marginally at the 68% c.l..

The non-thermal flux derived from the combined spectrum, $(1.5\pm0.5)\times10^{-11}$ erg cm^{-2} s^{-1} in the 20–80 keV energy range, is consistent with our previously published detection of $(2.2\pm0.8)\times10^{-11}$ erg cm^{-2} s^{-1} and with the value of $(1.2\pm0.3)\times10^{-11}$ erg cm^{-2} s^{-1} measured by *RXTE* in the same energy band (Rephaeli, Gruber, & Blanco 1999) and confirmed by a second deeper observation (Rephaeli & Gruber 2002). The non-thermal flux value and the relative c.l. of the excess have been obtained using the *Ginga* measurement of 8.11±0.07 keV (David *et al.* 1993) for the average gas temperature that is in good agreement with the *XMM-Newton* determination (Arnaud *et al.* 2001) of 8.25±0.10 keV in the central region (R$< 10'$) of the cluster. In fact, all the X-ray observations of Coma (Hughes, Fabricant, & Gorenstein 1998a; Hughes *et al.* 1988b; Watt *et al.* 1992; Hughes *et al.* 1993) have indicated a clear pattern: the larger the field of view, the lower the measured temperature. Besides, *RXTE* reports a best-fit temperature of 7.90±0.03 keV (Rephaeli & Gruber 2002) in a field of view of $\sim 1^\circ$ comparable to that of the PDS. However, also considering kT=8.25 keV for the average gas temperature in the field of view of the PDS, the non-thermal excess is at the level of $\sim 4.6\sigma$ (observed count rate = 0.349±0.015 cts/s, model predicted rate = 0.280 cts/s) and the derived non-thermal flux has a negligible variation.

Recent PDS data analysis of Coma performed with the SAXDAS software have lead to controversial results: an analysis of both observations has not reported evidence for a non-thermal excess (Rossetti & Molendi 2003), while the analysis of the first one (OBS1) by Nevalainen *et al.* (2003) confirms our published HXR detection, albeit at lower confidence level for the systematic uncertainties of their work. A systematic comparison between PDS spectra extracted by means of the two software packages (XAS, used here, and SAXDAS) is under way (Landi *et al.* , 2003). Preliminary results on the analysis performed on sources of different luminosities show that the spectral parameters do not change when computed with different packages. On the other hand, the errors associated to the spectral parameters are smaller when using XAS. This effect is more accentuated for faint sources. We suspect that this could be due to differences in filtering of good data and/or in the spectral equalization (i.e., conversion from spectral channels to energy channels) that for SAXDAS is performed *after* summing the four PDS units while for XAS is performed *before*. These effects will be

discussed into details in a forthcoming paper (Landi *et al.* in preparation).

As discussed in the Introduction, the likely origin of the non-thermal HXR excesses detected by *BeppoSAX* and *RXTE* is IC emission by the same relativistic electrons responsible for the diffuse radio emission scattering the CMB photons, as predicted in the 1970's (see Perola & Reinhardt 1972; Rephaeli 1979). The probability to find obscured sources in the field of view of the PDS may be lower than $\sim 10\%$, as estimated by Kaastra *et al.* (1999) and Fusco-Femiano *et al.* (2002), considering that non-thermal HXR emission has been detected in at least two clusters, Coma and A2256, both showing extended radio emission. A detailed search by Nevalainen *et al.* (2003) excludes a significant contamination from obscured AGN present in the FOV of Coma and A2256 and supports an indication for an extended non thermal emission. If we take into account the estimated contribution by AGN in Coma: $(9\pm6)\times 10^{-3}$ cts/s in the 20–80 keV energy range, the confidence level of the non-thermal excess is in the interval $\sim (3.9 - 4.7)\sigma$.

In the framework of the IC model the combination of the radio and non-thermal X–ray fluxes allows an estimate for a volume-averaged intracluster magnetic field B_X of $\sim 0.2\mu G$ (see Fusco-Femiano *et al.* 1999). This value seems to be in contrast with the line of sight magnetic field derived from the Faraday rotation of polarized radiation of sources through the ICM ($B_{FR} \sim 6\mu G$; Feretti *et al.* 1995). Newman, Newman & Rephaeli (2002) have recently pointed out that many and large uncertainties are associated with the determination of B_{FR} (see also Govoni *et al.* 2002 and Govoni & Murgia 2003). However, this discrepancy can be attenuated by considering models that include the effects of more realistic electron spectra, spatial profiles of the magnetic fields and anisotropies in the pitch angle distribution of the electrons (Goldshmidt & Rephaeli 1993; Brunetti *et al.* 2001; Petrosian 2001; Kuo, Hwang, & Ip 2003). The present value of the non-thermal HXR flux is slightly lower than that reported in Fusco-Femiano *et al.* (1999) favoring a central magnetic field strength of 1–2 μG in the *two-phase* model of Brunetti *et al.* (2001), more consistent with the B_{FR} values.

The alternative between primary and secondary electrons as responsible for non-thermal phenomena in clusters of galaxies is discussed in many papers. Primary electrons may be injected in the ICM of the Coma cluster by some processes (starbursts, AGNs, shocks, turbulence) during a first phase and re-accelerated during a second phase (Brunetti *et al.* 2001). Secondary electrons may be due to decay of charged pions generated in cosmic ray collisions within the ICM (Dennison 1980; Blasi & Colafrancesco 1999; Dolag & Enßlin 2000; Miniati *et al.* 2001; Miniati 2003). Radio and HXR spectral properties of Coma provide observational constraints able to discriminate between these two different populations of electrons (Brunetti 2002). In particular, the derived volume-averaged intracluster magnetic field of $\sim 0.2\mu G$ implies relativistic electrons at energies $\gamma \sim 10^4$ to explain the observed diffuse

synchrotron emission. At these energies IC losses may determine a cutoff in the spectrum of the accelerated electrons as supported by the radio spectral cutoff observed in Coma (Deiss *et al.* 1997). The cutoff in the electron spectrum may be naturally accounted for in the context of re-acceleration models, while it is not expected if the radio emission is due to a continuous production of secondary electrons. More recently, a radio spectral cutoff has been found also in the case of A754 by relating the VLA observation at 1.4 GHz (Bacchi *et al.* 2003) to the observations of Kassim *et al.* (2001) at lower frequencies. This cluster also shows non-thermal HXR radiation detected at a confidence level slightly above 3σ by *BeppoSAX* (Fusco-Femiano *et al.* 2003) and the derived value of the magnetic field is of the same order of that determined in Coma. The PDS detection should be confirmed by a deeper observation with imaging instruments for the presence of the radio galaxy 26W20 located at a distance of $\sim 27'$ from the *BeppoSAX* pointing. IBIS on-board *INTEGRAL* with its spatial resolution of $\sim 12'$ has the possibility to eliminate this ambiguity and to detect the excess at a higher confidence level with respect to that obtained by *BeppoSAX*.

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Table 1. Non-thermal HXR excess in 20–80 keV PDS observations[a]

	Epoch	PDS exposure (ksec)	Observed rate (cts/s)	Predicted rate (cts/s)	Excess (c.l.)	Flux[b]
OBS1	Dec 1997	44.5	0.390 ± 0.033	0.278	3.4σ	2.3 ± 1.0
OBS2	Dec 2000	122.2	0.333 ± 0.017	0.275	3.4σ	$1.3^{+0.5}_{-0.6}$
	Combined	166.7	0.349 ± 0.015	0.276	4.8σ	1.5 ± 0.5

Note. — Quoted errors at 90% confidence level for a single parameter.

[a] Excess with respect to a 8.1 keV (David *et al.* 1993) thermal bremsstrahlung component for energies above 20 keV (see text for details).

[b] In units of 10^{-11} erg cm^{-2} s^{-1} . A photon index of 2 was used to derive the flux (see text for details).

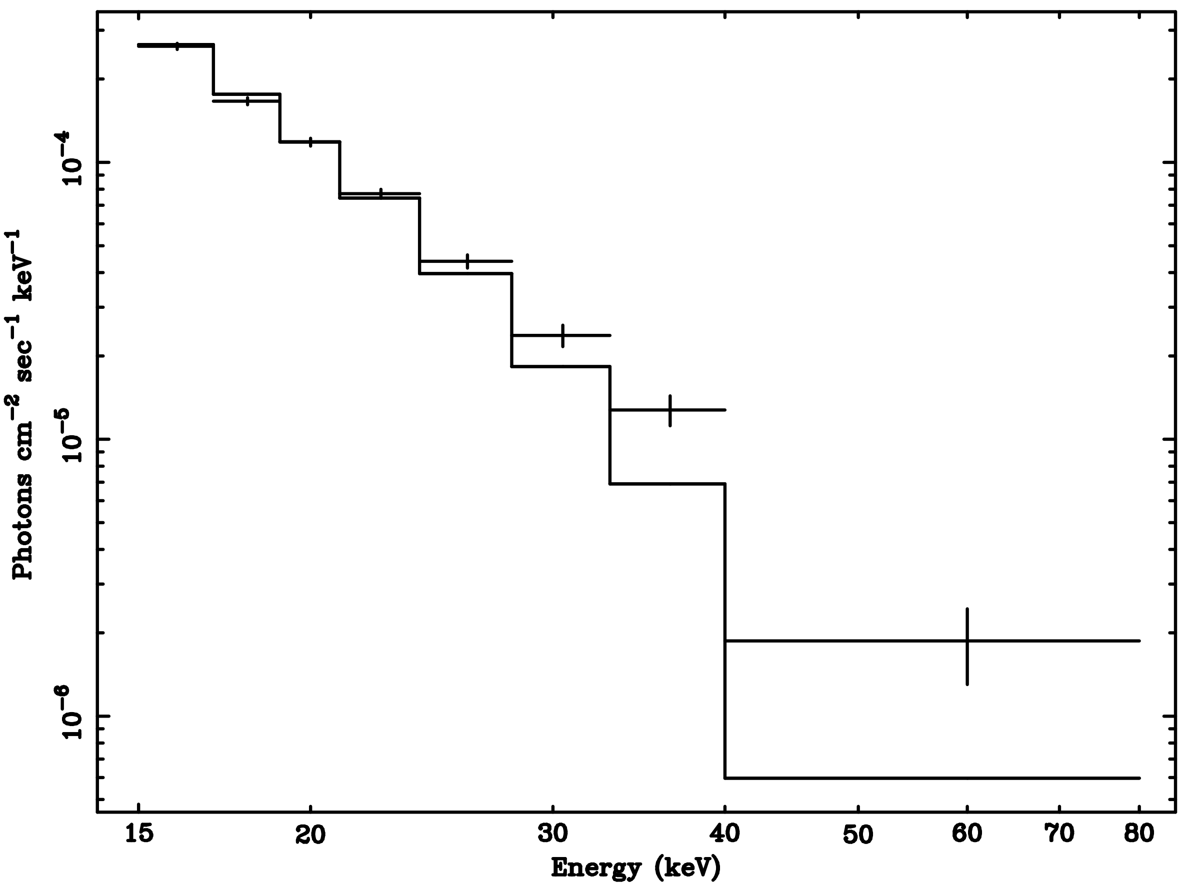

Fig. 1.— Coma cluster — PDS data. The continuous line represents the best fit with a thermal component at the average cluster gas temperature of 8.1 keV (David *et al.* 1993). The errors bars are quoted at the 1σ level.